Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

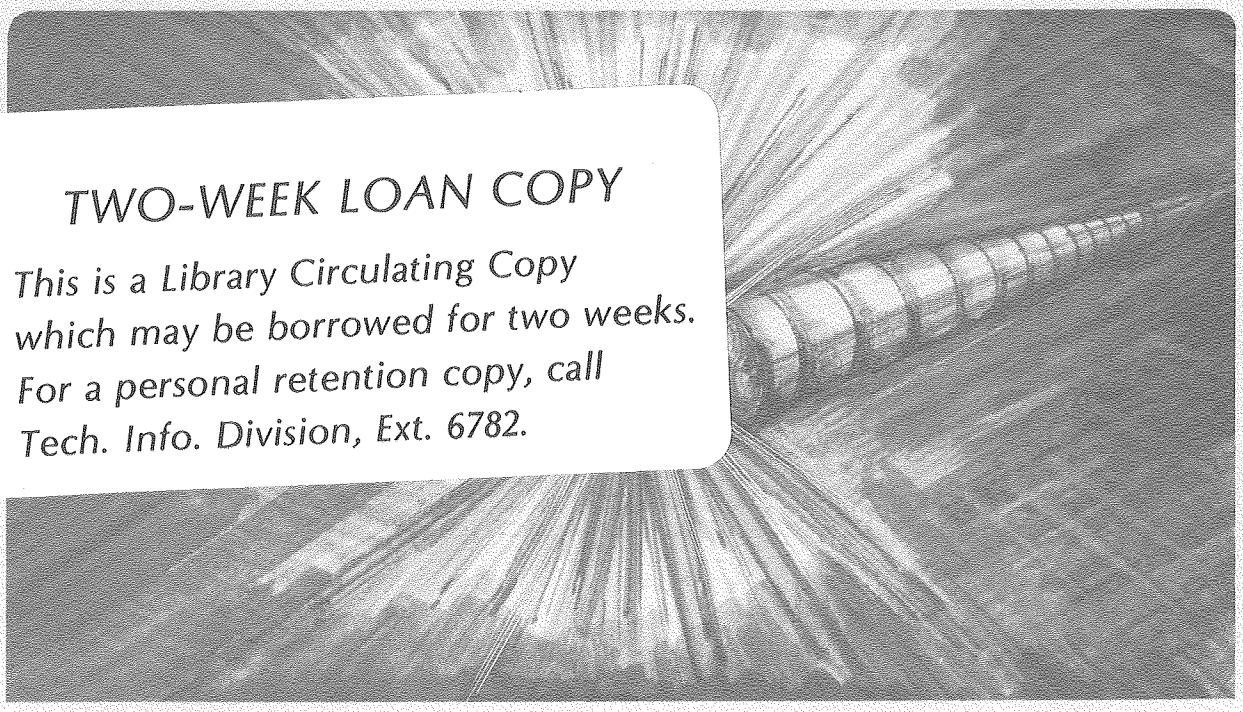
Accelerator & Fusion
Research Division

Presented at the MARIA Workshop III: Accelerator Systems for Relativistic Heavy Ions in Medical and Scientific Research, Edmonton, Alberta, Canada October 20-24, 1980

DEDICATED HEAVY ION MEDICAL ACCELERATORS

R.A. Gough

October 1980



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LBL-11808

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This paper outlines technological considerations in the design of accelerator facilities for medical applications. Emphasis is placed on the specific requirements for MARIA, a radioisotope and radiotherapy facility being planned in Edmonton, Canada. The material draws heavily on LBL experience (refs. 1,2,3) and addresses various accelerator components, including ion sources, injectors and synchrotrons. Requirements for the control system and considerations of facility layouts are also discussed.

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Dedicated Heavy Ion Medical Accelerators

R.A. GOUGH

Introduction

Five years ago the Lawrence Berkeley Laboratory, in collaboration with the University of Arizona, began a two-year design study which culminated in December 1977 with the publication of a final report (ref. 1) As part of this study a broad range of technological accelerator options was assessed to meet a variety of medical requirements. Its scope was specifically limited to facilities dedicated to the medical community with particular emphasis placed on the radiotherapeutic treatment of cancer in humans. Since this study there have been advances in accelerator technology and in biological understanding for the production and clinical application of relativistic heavy ions. The material presented here therefore will expand the ideas of the Berkeley/Arizona study to incorporate more recent information and experience, and to adapt this material to the needs of MARIA.

Present Experience at Berkeley

There is an extensive and active biomedical program at Berkeley (refs. 2,3) with an emphasis on various aspects of cancer medicine including radiotherapy and related radiobiological studies with heavy ions. Among the elements of this program are

- o radiotherapy
- o ablation of focal lesions
- o radiography
- o radioactive beams
- o fundamental studies in radiobiology and biophysics
- o isotope production.

At the Lawrence Berkeley Laboratory the accelerator needs in these areas are currently being met with the Bevalac, the 184-Inch Synchrocyclotron, and the 88-Inch Cyclotron. The main biomedical use of the 88-Inch

accelerator is for isotope production, while the Bevalac and 184-Inch provide the higher energy beams used in the bulk of the biomed program.

It is noteworthy that all three of these accelerators were designed primarily for physics research and that the 88-Inch and Bevalac continue to be shared with the physics and nuclear science communities. The 184-Inch, however, has now been converted for exclusive medical use, and it provides the 230 MeV/amu He beam used extensively by the radiotherapy program. It is an excellent example of the high level of reliability that can be achieved when an accelerator is reserved for exclusive medical use, and when 24 hour, 7 day/week operation is not needed; over the last several years, with an exceedingly modest operations and maintenance staff, a dependability of 98+% has been consistently maintained. A failure mode analysis of 184-Inch operations is shown in Table 1.

TABLE 1

184-Inch Failure Mode Analyses

A)	July 1977 - June 1978	1018.5 total operating hours
	1. Auxiliary Dee Water Flow	.75 hrs
	2. Finishing Line Pressure	0.25
	3. Main Coil Oil Pressure	0.25
	4. High Voltage Rectifier Relay	1.00
	5. Ion Source Filament Driver Chassis	.25
	6. Oscillator Pulsing Chassis	0.75
	7. Auxiliary Dee Water Filter	0.50
	8. High Voltage Rectifier Interlock	0.25
	9. Tank Vacuum	0.50
	10. Ion Source Filament Changes	1.00
	Total Down Time	5.50 hrs
	Percent Down Time =	5.50 / 1018.5 = 0.54%
B)	July 1979 - June 1980	976.25 total operating hours
	1. Oscillator Ground Contactor	0.25 hrs
	2. 1250 kW Generator Bearing Temperature	3.00
	3. Main Magnet Current Regulator Chassis	2.50
	4. Vibrating Reed #1 Driver Transistor	0.75
	5. Lower Main Coil Tank Oil Level	0.50
	6. DP2 Gate Valve	0.25
	7. Steering Magnet Control Chassis	1.75
	8. 2 MW Generator (loose brush)	4.25
	9. Main Coil Shunt Switch	0.50
	Total Down Time	13.75 hrs
	Percent Down Time =	13.75 / 976.25 = 1.4%

Figure 1 shows a schematic layout of the Bevalac complex used primarily for ions of carbon and heavier. It comprises the Bevatron, a weak-focusing synchrotron, as the main accelerator; a local injector, typically used for ions of carbon or lighter; the SuperHILAC, a highly versatile linac with three independent pre-injectors; and an experimental hall which accommodates users from many disciplines. The Biomedical area, shown more clearly in Figure 2, consists of three exposure rooms, two preparation rooms, and special facilities for radiography, radiological physics, and for tumor, tissue, cellular, molecular, neuro-developmental, and space radiobiology. In order to facilitate all aspects of the Biomed program and, in particular, to handle increased patient loads, it is now possible to switch the beam reliably from Cave I to Cave II in about a minute, including time for beam shaping and verification.

The clinical ambience required in the patient areas is quite different from the environment we usually associate with physics accelerators. Figures 3 and 4 illustrate how the Bevalac has adapted to these concerns; they show a patient treatment room, with a Philips couch to position the patient accurately and comfortably, and a waiting room which resembles the waiting area in a doctor's office or hospital.

The control room for the Biomed area, which is shown in Figure 5, is a very important aspect of our (or any future) facility, and its importance should not be underestimated.

Accelerator Components for a Medical Facility

During the earlier design study, an emphasis was placed on the production of carbon and neon beams for radiotherapeutic applications. Since that time, the Berkeley community has benefitted from radiobiological studies and clinical trials with heavier beams; the implications of this research point toward a facility that could accelerate silicon, or perhaps argon, as the heaviest ion. It seems clear, however, that no single "universal ion" will be preferred in all clinical situations, but rather, that an optimal treatment facility should be capable of producing several lighter ion species such as carbon, oxygen and neon. These lighter ions may be best for treatment of certain tumors

and also have a longer range capability suitable for radiographic imaging. A summary of the beam requirements for MARIA appears in Table 2.

TABLE 2

Heaviest Ion	Argon
Maximum kinetic energy	1 GeV/amu
$B\rho$:	125 kG m
Average Particle Flux	10^9-10^{10} particles/sec
Transverse emittance:	1-2 X 10^{-5} m-rad
Max. energy spread ($\Delta E/E$)	4 X 10^{-3}
Repetition rate:	1-2 Hz
Duty factor	25-50%

These specifications will permit treatment of large tumors in 2-3 minutes or less; furthermore, the intensities are sufficient to generate useful quantitites of radioactive beams (e.g. ^{19}Ne) for dose localization purposes.

To meet these specifications there are a number of possible technological options: the ion source, the injector, the synchrotron, and the control system merit special attention.

Ion Sources

Since there is a section scheduled later in the Workshop to discuss both traditional and advanced ion source concepts, I shall limit this discussion to just a few remarks. It is crucial that an ion source with assured high reliability be incorporated into the design of MARIA. This reliability factor plus the need, for example, to switch quickly from carbon to silicon could be achieved with a multiple PIG source arrangement. Such a device, shown in Figs. 6 and 7, has been developed by Gavin and his co-workers for the SuperHILAC Third Injector (ref. 6); its sources operate independently and either unit can be remotely positioned in front of the extractor electrode. The sputtering electrode technique for solid-material source-feed that has been developed at Berkeley (ref. 7) is particularly well-suited to the production of Si beams. Established PIG source technology (refs. 6,7) can easily produce the heavy ion beams needed by Maria. Table 3 illustrates PIG source performance for selected ions. Note that though this source performance represents intensities that have been available for many years (for example at the

SuperHILAC), improved PIG sources now being tested at Lawrence Berkeley Laboratory demonstrate considerably higher output intensities.

TABLE 3

Presently Available PIG Source/Performance

Ion			Current*
Carbon	4+	(Bevatron)	1500 μA
Neon	4+	(SuperHILAC)	700 μA
Silicon	4+	(SuperHILAC)	500 μA
Argon	6+	(SuperHILAC)	500 μA

*Electrical microamperes at source exit

Injector Considerations

A cyclotron is one injector option which might be attractive if radioisotope production or neutron therapy are considered important functions of the facility. However, rather than using a special cyclotron as the main injector, a more sensible approach might be to purchase a commercially available cyclotron dedicated to the production of radio pharmaceuticals. In this way, operations and maintenance staffs, as well as buildings and utilitiies, could be shared with facilities specifically fitted to meet the diverse medical needs. The cyclotron could then be used as an alternative injector for protons without much added expense.

Intensity requirements for heavy ions can most easily be met with a linac injector. In the earlier design study, both carbon and neon linacs seemed capable of meeting the medical requirements for those ions. Recent developments in RFQ technology, however, may make the RFQ linac an attractive option for the injection of a medical synchrotron because of its operational simplicity, low power consumption, overall compactness, and modest preinjector requirements. These ideas will be covered more thoroughly later in the Workshop.

Synchrotron

The best choice for the main accelerator of MARIA appears to be a conventional synchrotron. The ring would have approximately a 17 m radius, consist of normal-conducting magnets and have one or perhaps two

RF accelerating cavities. Techniques of resonant extraction could be used to provide a slow and uniform spill characterized by a 1 Hz rep rate and a 25-50% duty factor. Another option worth consideration is stripping extraction: acceleration of partially-stripped ions, although imposing stricter vacuum requirements, would permit a simple stripping-extraction scheme.

A possible set of accelerator parameters for argon beams is shown below.

TABLE 4

Preinjector	
Ion Source	Dual PIG at 50 - 100 kV
Output Current	200 microamperes of Ar^{6+}
Injector	
RFQ linac	4 MeV/amu
Alvarez linac	4-8 MeV/amu
Synchrotron	
Vertical gap	4 cm
Horizontal aperture	10 cm
Magnet length	2-3 cm
Magnetic field	10 kG
Maximum frequency	2.83 MHz
Rep Rate	1 Hz
Accelerating voltage / turn	23 kV
Ring Radius	17 m
Max Beam Energy	1 GeV/amu

Such a facility could also accelerate other ions up the magnetic rigidity of 125 kG m. For ions lighter than argon, a penetration through tissue in excess of 30 cm would be feasible. Ions heavier than argon could be produced, but their range in tissue would be limited by the synchrotron to 30 cm, and their intensities would be limited by the ion source and the injector.

A further point to consider in the choice of particle species is that if the MARIA facility is also to accelerate protons with intensities of 10^{11} protons/second then the radiation shielding costs will be considerably higher. For a versatile facility, movable shielding should be used where feasible, and crane access and staging areas should be provided.

Control System

If MARIA is to have maximum reliability and minimum downtime, careful planning of the control system is absolutely necessary. Planning is especially critical in order to provide flexibility for user multiplicity and pulse-to-pulse energy or particle species variability. The requirements of the therapy technician must be thoroughly integrated with the overall control system; operators must be able to call up information quickly and easily, and be able to monitor every aspect of machine operation and treatment delivery. Efficient communication must be possible between the users and all personnel associated with the machine operation.

The control system should be able to:

1) perform beam tuning and monitoring functions
2) report status of all components of the facility
3) detect, diagnose, and report malfunctions of any components of the facility--including components of the computer system itself
4) provide information to the operations staff regarding precise location and inventory of spare parts
5) archive and recall operational records of the accelerator, the beam delivery system, and patient treatments
6) be updated simply and easily without interfering with daily operations.

There are many approaches to the design of a control system, and it is often best to trust to the experience of a competent computer design group. However, the critical importance of the control system for MARIA must be paramount in any design considerations, and it clearly demands a constant, continuing assessment and coordination by all members of the design team.

Facility Layout Considerations

The layout of the beam delivery components and transport system needs careful planning. Specific areas should be clearly separated to maintain an appropriate clinical environment for patients (free from animal odors

and unsightly physicists), and to isolate the radioisotope area to ensure safe handling of high levels of radioactivity.

Superconducting magnets might be used for beam transport and delivery to reduce space and operating costs; however, these potential advantages must be weighed against the added maintenance burden and possible unreliability of this technology.

The treatment port orientations and beam line layouts must allow for crane access for all magnets should they need to be removed or replaced. This is especially true in planning a beam port which directs the beam vertically upward from beneath the patient.

To instill a proper respect for the rigidity of relativistic heavy ion beams, Figure 8 shows the size of a possible gantry system for a 415 MeV/amu beam. The facility layout shown in Figure 9 was prepared for a 415 MeV/amu carbon facility during the design study. There is no provision for an isocentric gantry in this facility. Since MARIA will be designed for beams of twice the rigidity, its plans should allow for a proportionally larger layout. Furthermore, the overall compactness of this carbon facility was essential for its possible placement in an existing hospital. MARIA should not be unduly limited by inadequate space; if past experience is an adequate guide, a standard rule should be to make your best estimate for the space required, and then double it.

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7 E. Zajec and R.M. Richter, "Heavy Ion Source Development at the Bevataron," IEEE Trans. on Nucl. Sci., NS-26 (1979) 2061.

Figure Captions

1. Schematic layout of the LBL Bevalac Complex.

2. Schmatic layout of the biomedical facility at the LBL Bevalac.

3. Patient treatment room at the Bevalac.

4. Patient waiting room at the Bevalac.

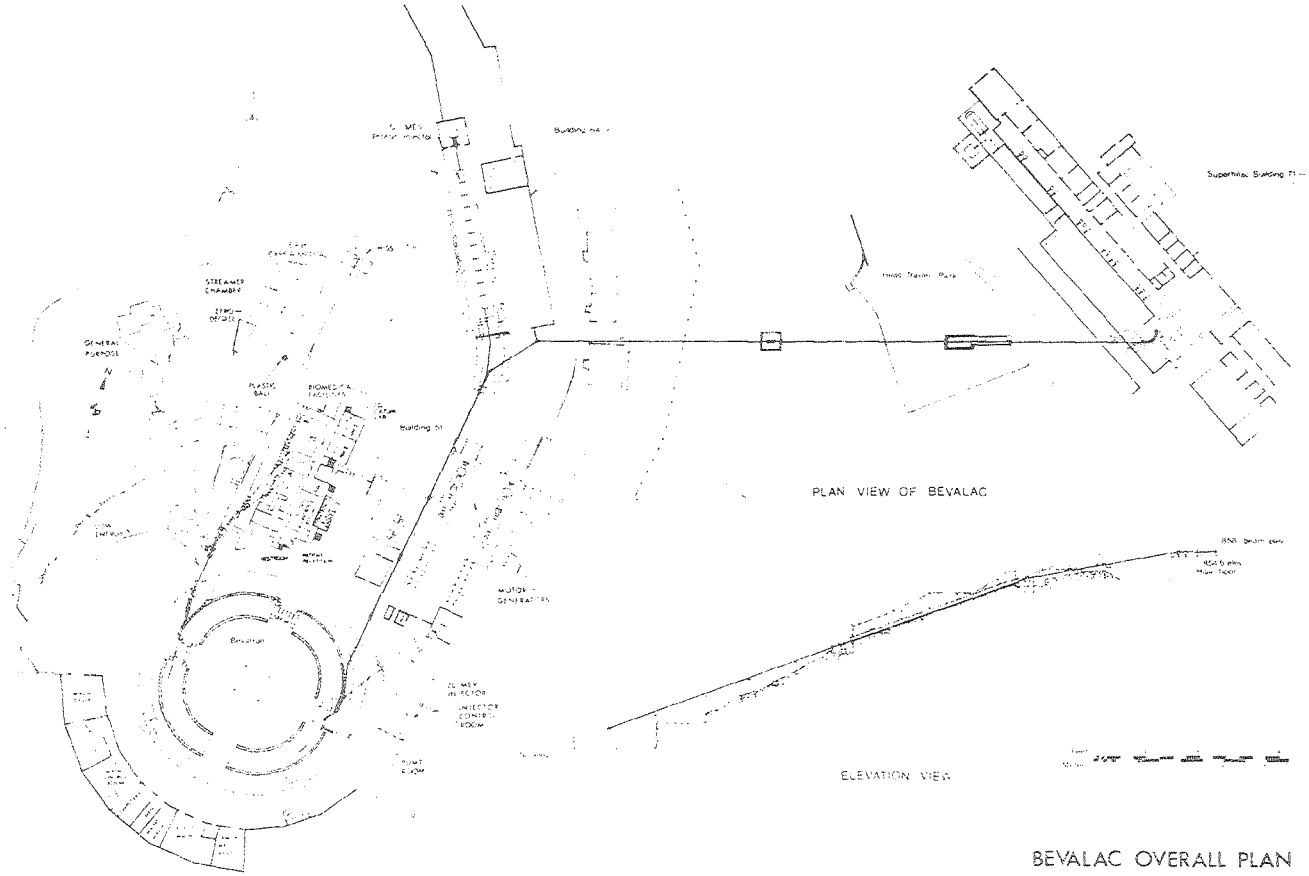
5. Biomedical control console at the Bevalac.

6. Dual PIG sources for the SuperHILAC Third Injector.

7. Dual PIG sources shown mounted in the source magnet prior to installation in the SuperHILAC Third Injector.

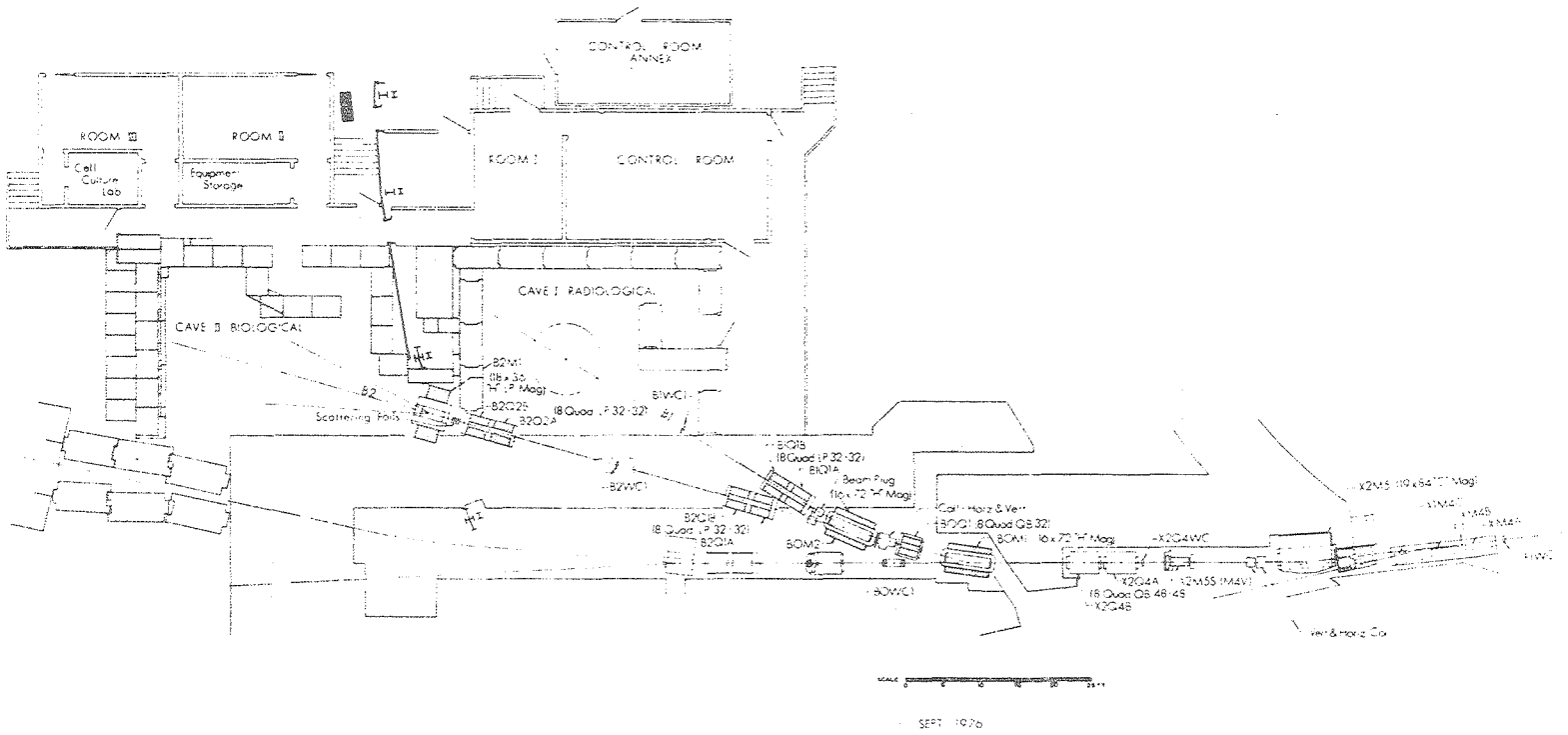
8. An isocentric gantry for delivery of a 415 MeV/amu carbon beam.

9. Layout of a 415 MeV/amu carbon beam medical accelerator facility.



BEVALAC OVERALL PLAN

Figure 1



BIOMEDICAL BEAM B1 & B2

XBL 773-7883A

Figure 2

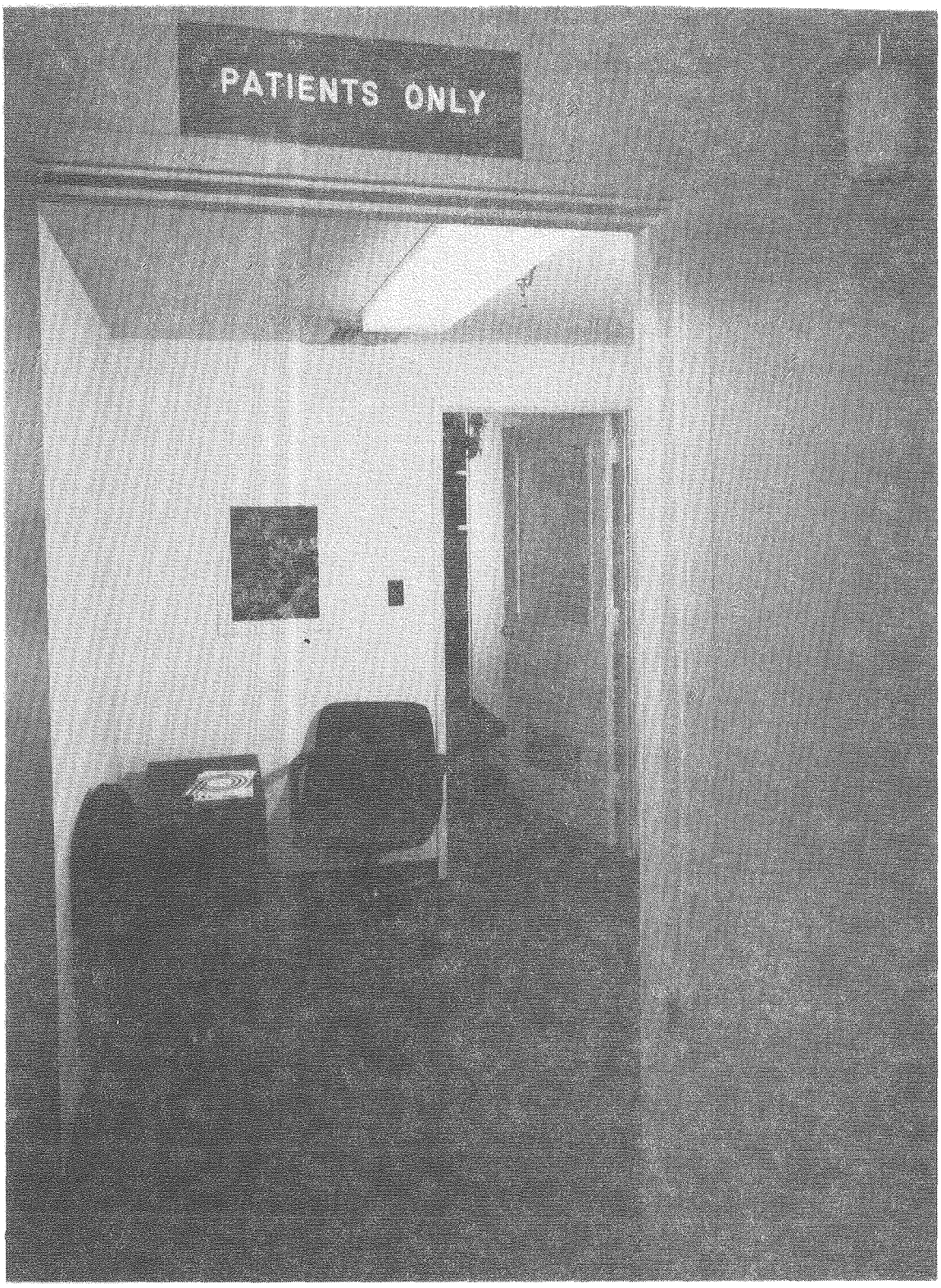


Figure 3

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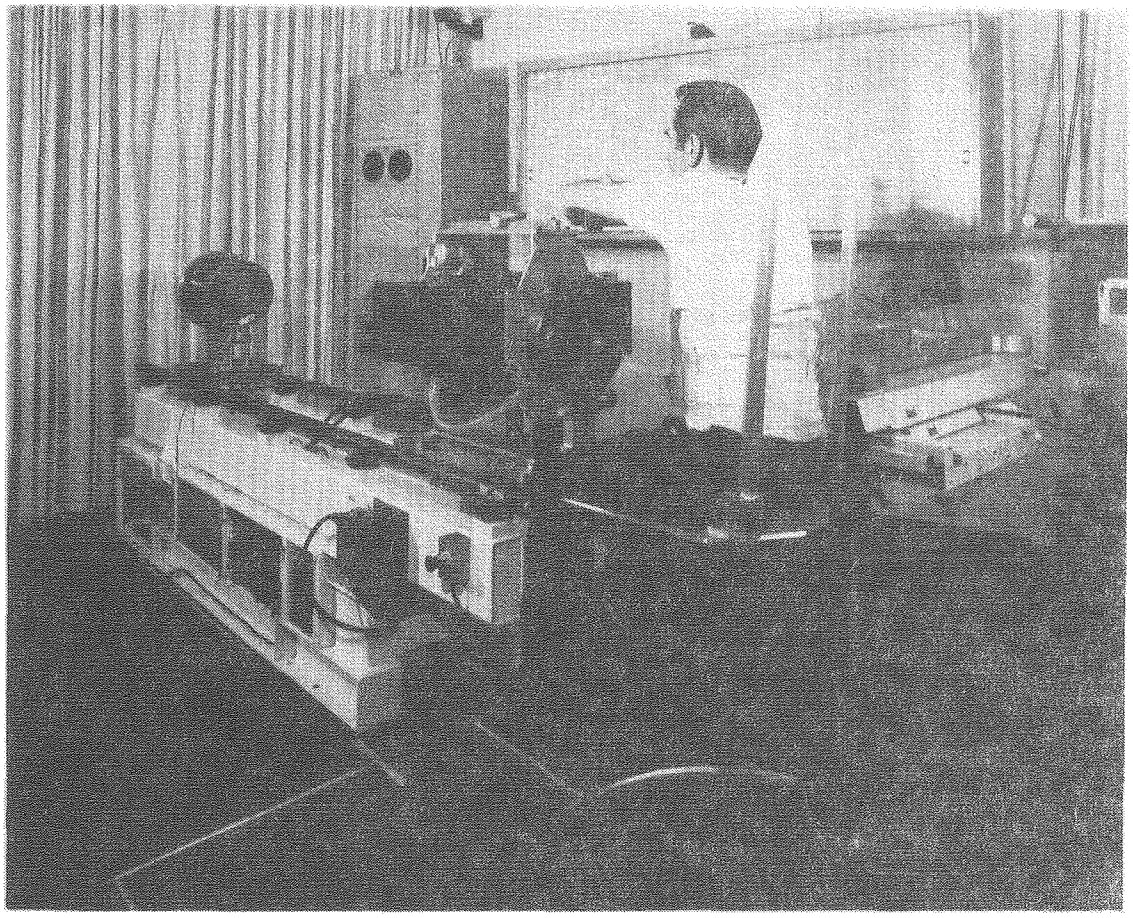
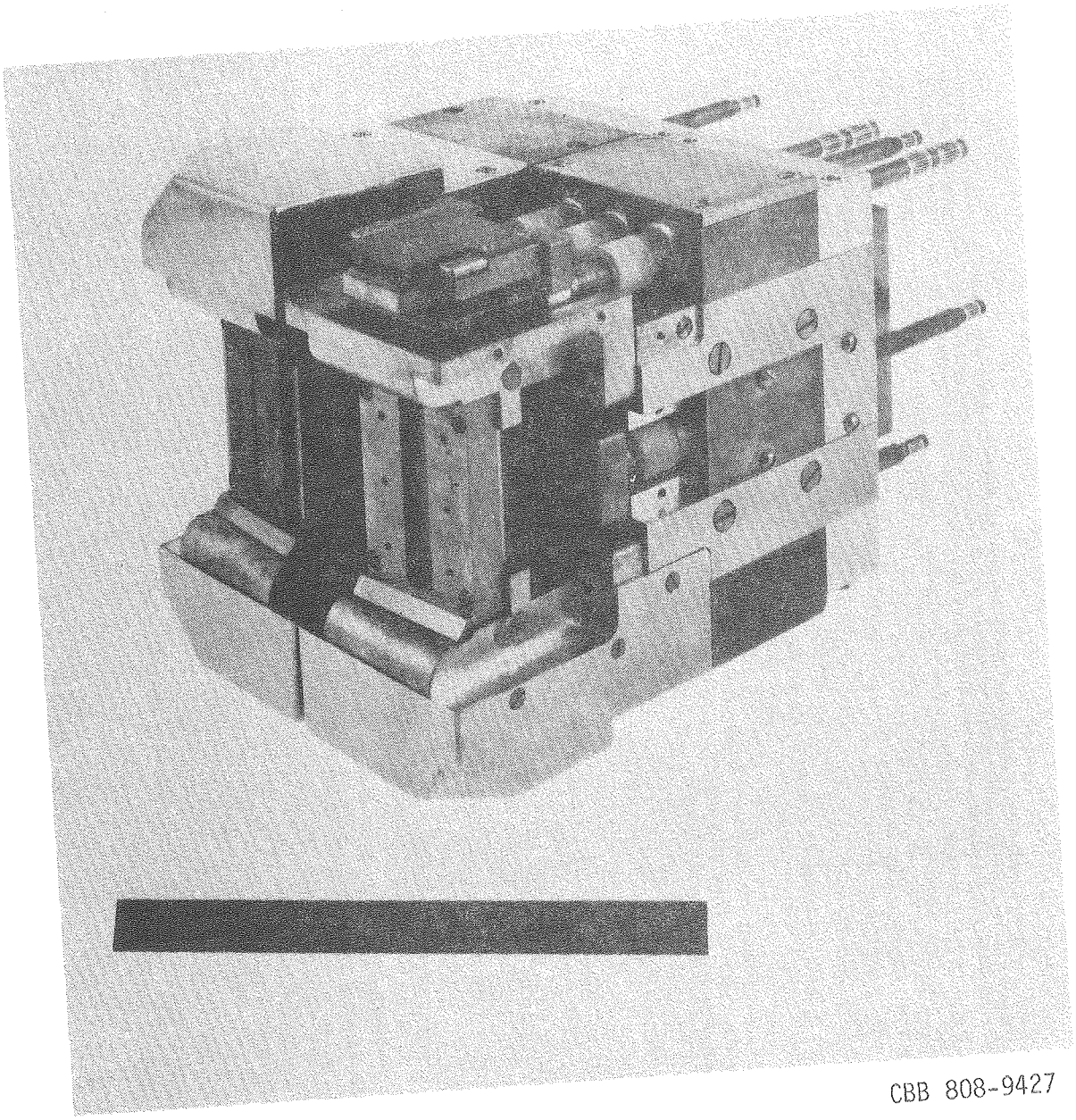


Figure 4 CBB 7810-13486

Figure 5 CBB 788-10246



CBB 808-9427

Figure 6

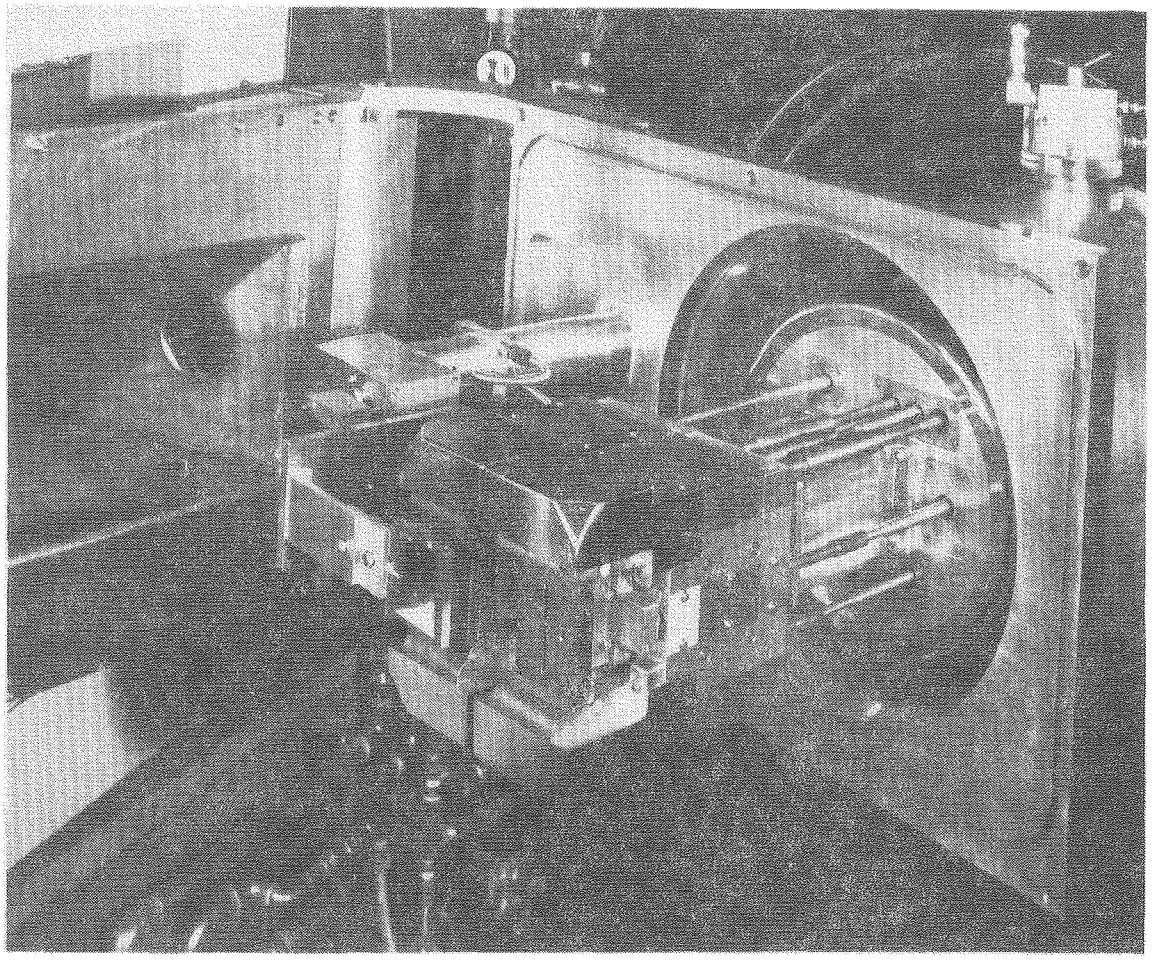
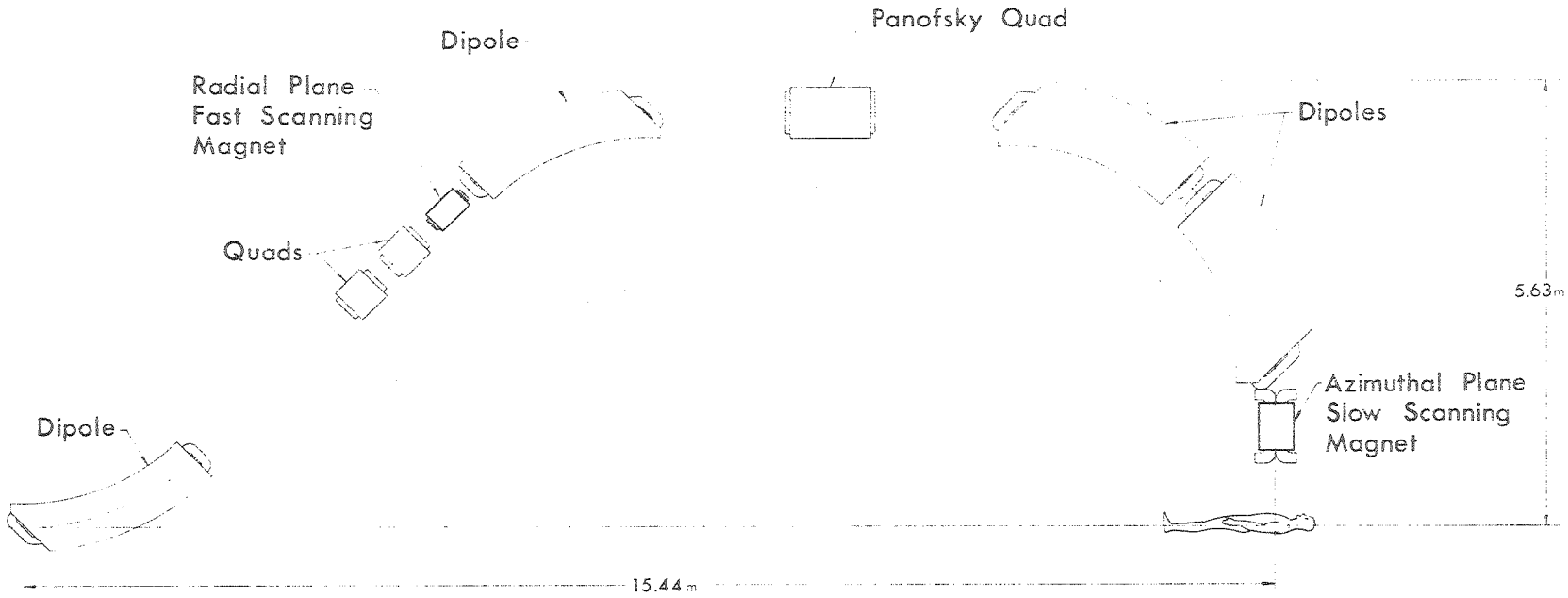


Figure 7 CBB 808-9435

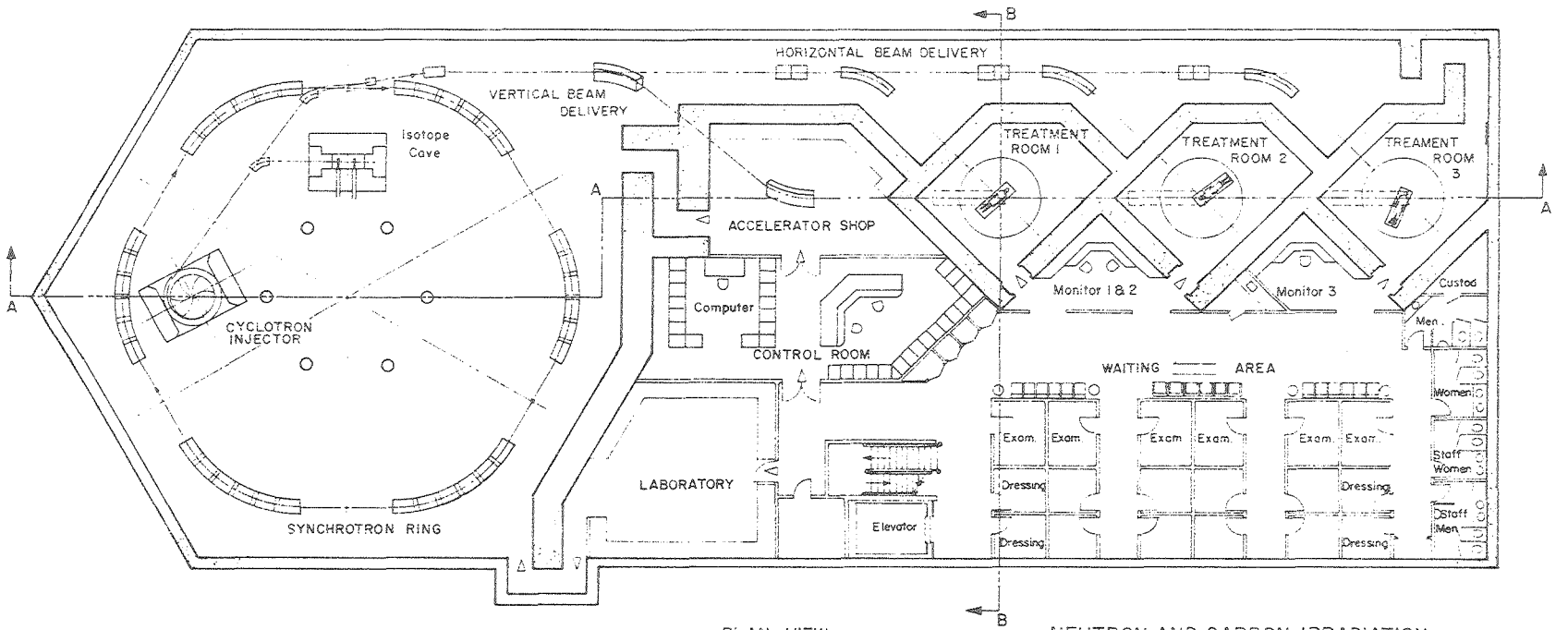


ISOCENTRIC BEAM DELIVERY LINE INCORPORATING A SCANNING SYSTEM

Scale 0 1m 2m 3m 4m 5m

XBL 772-7800

Figure 8



NEUTRON AND CARBON IRRADIATION THERAPY FACILITY
CONCEPT DRAWING

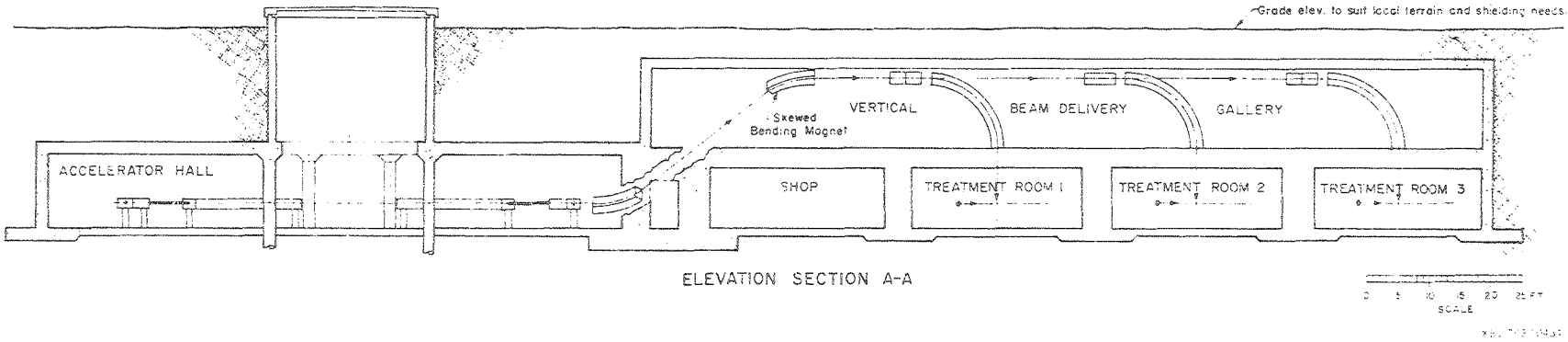


Figure 9